

T -Odd Effects in Unpolarized Drell-Yan Scattering

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We consider the leading twist T -odd contributions as the dominant source of the $\cos 2\phi$ azimuthal asymmetry in unpolarized $p\bar{p} \rightarrow \mu\mu^+ X$ dilepton production in Drell-Yan Scattering. This asymmetry contains information on the distribution of quark transverse spin in an unpolarized proton. In a parton-spectator framework we estimate these asymmetries at 50 GeV center of mass energy. This azimuthal asymmetry is interesting in light of proposed experiments at GSI, where an anti-proton beam is ideal for studying the transversity properties of quarks due to the dominance of *valence* quark effects.

1. Introduction

One of the persistent challenges confronting the QCD parton model is to provide a theoretical basis to understand the experimentally significant azimuthal and transverse spin asymmetries that emerge in exclusive, inclusive and semi-inclusive processes [1,2,3,4,5,6]. Generally speaking, the spin dependent amplitudes for the scattering will contribute to non-zero transverse single spin asymmetries (SSA) if there are imaginary parts of bilinear products of those amplitudes that have overall helicity change. For two-body exclusive reactions, SSA requires there to be an imaginary part of the product of an helicity non-flip with an helicity flip amplitude. For inclusive reactions, the same conclusion can be reached by taking the amplitudes as two-body helicity amplitudes for the production of a fixed hadron and a state $|X\rangle$. Through the generalized optical theorem, SSA in inclusive reactions can be related to discontinuities in helicity flip three-body forward scattering amplitudes [7]. That is essentially spin kinematics. Dynamically there must be quantum field theory contributions to the relevant amplitudes. In perturbative QCD (PQCD), applicable to the hard scattering region, to obtain an imaginary contribution to quark and/or gluon scatter-

ing processes demands introducing higher order corrections to tree level processes. One approach incorporates the requisite phases through interference of tree level and one-loop contributions in PQCD in an attempt to explain spin asymmetry in Λ production [8]. On general grounds the helicity conservation property of massless QCD predicts that such contributions are small, going like $\alpha_s m/Q$, where α_s is the strong coupling, m represents a non-zero quark mass and Q represents the hard QCD scale [9,8]. Such contributions have failed to account for the large SSA observed in Λ production [1]. On the other hand, the twist three quark-quark and quark-gluon correlations described in [10] and [11] hold promise to describe the phenomena at large p_T .

However, considering the soft contributions to hadronic processes opens up the possibility that there are non-trivial transversity parton distributions that can contribute to transverse spin asymmetries. Ralston and Soper introduced [12] the now well known chiral-odd transversity transfer distribution function [13,14] $h_1(x)$ which can play a role in doubly polarized Drell-Yan processes [15]. $h_1(x)$ can also be measured in semi-inclusive deep inelastic scattering (SIDIS) [16]. For SSA in SIDIS transverse momentum must be acquired to lead to appropriate helicity changes. In describing transverse asymmetries this is par-

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ticularly important when the transverse momentum is sensitive to intrinsic quark momenta. Here the effects are associated with non-perturbative transverse momentum distribution functions [17] (TMD), where transverse single spin asymmetries indicate so called T -odd correlations between transverse spin and longitudinal and intrinsic quark transverse momentum. The T -odd distributions [18,19,20] are of importance as they possess both transversity properties and the necessary phases to account for SSA and azimuthal asymmetries [16,21,22]. Formally, these phases can be generated from the gauge invariant definitions of the T -odd quark distribution functions [23,24,25,26]. Asymmetries that involve T -odd TMD and fragmentation functions are indicative of a rich set of correlations among transverse momenta of quarks and/or hadrons and the transverse spin of the reacting hadrons and/or quarks. In contrast to the SSA generated from the interference of tree-level and one loop correction in PQCD, such effects go like $\alpha_s \langle k_\perp \rangle / M$, where now M plays the role of the chiral symmetry breaking scale and k_\perp is characteristic of quark intrinsic motion.

T -odd distributions only exist by virtue of non-zero parton transverse momenta [19,27,20]. They also correspond to distributions that would vanish at *tree level* in any T -conserving model of hadrons and quarks. In this sense they are similar to the decay amplitudes for hadrons that involve single spin asymmetries which are non-zero due to final (and/or initial) state strong interactions. Their existence was suggested by Sivers to account for the significant SSA in inclusive reactions (*e.g.* $pp^\uparrow \rightarrow \pi X$) [18,19], by Collins in SIDIS [16], and by Boer [21] in Drell-Yan scattering.

A great deal of progress has been made in the last several years, following the realization that this link goes further, as Brodsky, Hwang and Schmidt first showed [22] and several researchers generalized thereafter [24,25]. Detailed model calculations of these functions have been performed in parton inspired spectator-models of quark-hadron interactions where absorptive effects are generated by interference between gluon loop corrections to tree-level TMDs. These loop

calculations were applied to SIDIS [22,24,28,25, 29,30,31,32] and Drell-Yan processes [33,34,35], thereby giving rise to predictions for SSA and azimuthal asymmetries.

The importance of quark distribution functions was recognized some 35 years ago by Drell and Yan [36] when they considered high energy hadron scattering that produces large invariant mass lepton pairs as a fundamental probe of quark-antiquark distribution functions. Furthermore, considering various asymmetries and polarization phenomena in Drell-Yan processes can uncover relevant products of spin dependent distributions [21]. Indeed, Drell Yan $p\bar{p}$ scattering is a preferred reaction to study the role that T -odd quark distribution functions play in the transverse spin structure of the proton through spin and azimuthal asymmetries in QCD [21]. That is the direction we pursue herein.

2. Drell-Yan and T -Odd Correlations

At the parton level the Drell-Yan cross section will receive contributions from quark-antiquark annihilation into the heavy photon. In unpolarized Drell-Yan scattering early cross section data as a function of the transverse momentum of the muon pair indicated deviations from the Bjorken scaling prediction [37,38]. The implication was that the collinear approximation was insufficient to describe the data [39,40]. Transverse momentum of a parton arises due to hard Bremsstrahlung of gluons, which is calculable from PQCD when the momentum transfers are large [41]. On the other hand, quark confinement implies that quarks have soft, primordial or intrinsic transverse momenta \mathbf{k}_\perp . This latter effect is significant at low transverse momentum, $q_T \ll Q$. q_T dependence has been incorporated into the factorized Drell-Yan model [12,42] by extending the parton probability distribution to be a function of \mathbf{k}_\perp [17]³

$$\int d\mathbf{k}_\perp \mathcal{P}(k_\perp, x) = f(x). \quad (1)$$

If the parton distributions within the incoming hadrons have transverse momentum dependence,

³New work on the factorization theorem for Drell-Yan can be found in [43].

there will be a continuum of values of their k_\perp for which a time-like photon of fixed 4-momentum will be formed. Ignoring or summing over spin (and the lepton pair orientation), the k_\perp dependent distribution functions appear in the differential cross section,

$$\frac{d\sigma}{dq^2 dy d^2 q_T} = \frac{4\pi\alpha^2}{3Q^4} \sum_a e_a^2 \int d^2 k_\perp \int d^2 p_\perp \delta^{(2)}(\mathbf{k}_\perp + \mathbf{p}_\perp - \mathbf{q}_T) f_{a/A}(x, k_\perp) \bar{f}_{\bar{a}/B}(\bar{x}, p_\perp)$$

where $f_{a/A}(x, k_\perp)$ is a distribution function for a quark a to be found in hadron A with transverse momentum \mathbf{k}_\perp and longitudinal momentum fraction x_1 and \bar{f} is the corresponding anti-quark distribution in hadron B .

Once transverse momentum dependence of parton distributions enters the picture of scattering processes a much larger set of transverse momentum distribution (TMD) and fragmentation functions[27] become possible and relevant, particularly for spin asymmetries. Among such functions are the possible leading twist T -odd quark distribution [18] and fragmentation functions [16].

In SIDIS with an unpolarized target, an expectation value of $i\mathbf{s}_T \cdot (\mathbf{P} \times \mathbf{k}_\perp)$, indicates a T -odd correlation of transverse quark polarization with the proton's momentum and the intrinsic quark transverse momentum in an unpolarized nucleon while $i\mathbf{s}_T \cdot (\mathbf{p} \times \mathbf{P}_{h\perp})$, corresponds to that of a fragmenting quark's polarization with quark and transverse pion momentum, $\mathbf{P}_{h\perp}$. These correlations enter the *unpolarized* cross-section through convolutions with h_1^\perp [20] and the Collins fragmentation function H_1^\perp [16]. The resulting $\cos 2\phi$ asymmetry is not suppressed by $1/Q$, where Q represents the scale in SIDIS - the T -odd contribution is at leading twist [20,29,30]. An analogous unpolarized double T -odd azimuthal asymmetry enters the Drell-Yan process [21]. For the Drell-Yan process the angular dependence can be expressed as

$$\begin{aligned} \frac{dN}{d\Omega} &\equiv \left(\frac{d\sigma}{dQ^2 dy d^2 q_T} \right)^{-1} \frac{d\sigma}{dQ^2 dy d^2 q_T d\Omega} \\ &= \frac{3}{4\pi} \frac{1}{\lambda + 3} \left(1 + \lambda \cos^2 \theta + \mu \sin^2 \theta \cos \phi \right. \\ &\quad \left. + \frac{\nu}{2} \sin^2 \theta \cos 2\phi \right). \end{aligned} \quad (2)$$

The solid angle Ω refers to the lepton pair orientation in the pair rest frame relative to the boost direction and the incoming hadrons' plane [42]. λ, μ, ν are functions that depend on $s, x, m_{\mu\mu}^2, \mathbf{q}_T$, the center of mass energy, the fraction of quark momentum in the hadron, the invariant mass of the produced lepton pair, and the transverse momentum of the dimuon pair.⁴

By keeping the Ω dependence in the convolution, Collins and Soper [42] could project out the photon angular dependence in Eq. (2) and obtain, among the other asymmetry functions, a (spin averaged) T -even contribution to the $\cos 2\phi$ asymmetry

$$\nu_4 = \frac{\frac{1}{Q^2} \sum_a e_a^2 \mathcal{F} [w_4 f_1(x, k_\perp) \bar{f}_1(\bar{x}, p_\perp)]}{\sum_a e_a^2 \mathcal{F} (f_1(x, k_\perp) \bar{f}_1(\bar{x}, p_\perp))}, \quad (3)$$

where $w_4 = 2(\hat{\mathbf{h}} \cdot (\mathbf{k}_\perp - \mathbf{p}_\perp))^2 - (\mathbf{k}_\perp - \mathbf{p}_\perp)^2$ and, $\hat{\mathbf{h}} = \mathbf{q}_T/Q_T$. Indeed the earliest theoretical explanation for azimuthal asymmetries was given by Collins and Soper's estimate of ν in Eq. (3), which is a kinematic non-leading twist contribution. However, all of the asymmetry functions, μ, λ and ν , were shown to have parton model contributions. Taking into account NLO [41] and NNLO [44] the QCD improved parton model predicts $1 - \lambda - 2\nu = 0$, the so called Lam-Tung relation [45]. However, experimental measurements of $\pi p \rightarrow \mu^+ \mu^- X$ discovered unexpectedly large values of these asymmetries [2,3] compared to parton-model expectations resulting in a serious violation of this relation. Attempts to account for the violation in terms of higher twist effects [46,47] have been unsuccessful. More recently, Boer [21] proposed that there is a dominant leading twist contribution to ν coming from the T -odd transversity distributions $h_1^\perp(x, k_\perp)$ for both hadrons which dominates in the kinematic range, $\mathbf{q}_T \ll Q$. The $\cos 2\phi$ azimuthal asymmetry in unpolarized $p\bar{p} \rightarrow \mu^+ \mu^- X$ would involve the convolution of the leading twist T -odd function, h_1^\perp [21,33,34,35]

$$\nu_2 = \frac{\sum_a e_a^2 \mathcal{F} [w_2 h_1^\perp(x, k_\perp) \bar{h}_1^\perp(\bar{x}, p_\perp) / (M_1 M_2)]}{\sum_a e_a^2 \mathcal{F} [f_1(x, k_\perp) \bar{f}_1(\bar{x}, p_\perp)]}$$

⁴We are working in the Collins-Soper frame where \mathbf{q}_T retains its meaning.

(4)

where $w_2 = (2\hat{\mathbf{h}} \cdot \mathbf{k}_\perp \cdot \hat{\mathbf{h}} \cdot \mathbf{p}_\perp - \mathbf{p}_\perp \cdot \mathbf{k}_\perp)$ is the weight in the convolution integral, \mathcal{F} [21]. A simple model for these distributions, inspired by Collins' ansatz for the transversity fragmentation function led to Q_T dependent ν which could be fit to the low values of the πp data. Further work along those lines [33,34,35] incorporated a more realistic model for the T -odd functions, as first developed in SIDIS [22] for the functions $f_{1T}^\perp(x, k_\perp)$ which were related to the $h_1^\perp(x, k_\perp)$ in ref. [25]. The results were presented for $p\bar{p}$ scattering.⁵ This azimuthal asymmetry is interesting in light of proposed experiments at Darmstadt GSI [50], where an anti-proton beam is ideal for studying the transversity property of quarks due to the dominance of *valence* quark effects [49]. Herein we extend our calculations for T -odd contributions to the unpolarized Drell-Yan Scattering first reported in [34]. We perform a detailed analysis displaying q_T and for the first time x, x_F , and q (or $m_{\mu\mu}$) dependence of this effect. In addition we compare the double T -odd contribution to the conventional subleading twist T -even contribution [42].

3. T -odd transversity distribution

For our purposes we consider h_1^\perp projected from the correlation function for the TMD function $\Phi(k, P)$,

$$\Phi(x, \mathbf{k}_\perp) = \frac{M}{2P^+} \left\{ f_1(x, k_\perp) \frac{P}{M} + h_1^\perp(x, k_\perp) \frac{i \mathbf{k}_\perp P}{M^2} + \dots \right\} \quad (5)$$

that is

$$\int dk^- \text{Tr}(\sigma^{\perp+} \gamma_5 \Phi) = \frac{2\varepsilon_{+-\perp j} k_{\perp j}}{M} h_1^\perp(x, k_\perp) \dots$$

In our work on SIDIS we used a parton model within the quark-diquark spectator framework to model the quark-hadron interactions that enter $\Phi(k, P)$ [25,29] and contribute to T -odd terms in the projection. The basic diagram, indicating the one loop gluon exchange and the eikonalized

⁵Very recently instanton induced effects have been investigated [48].

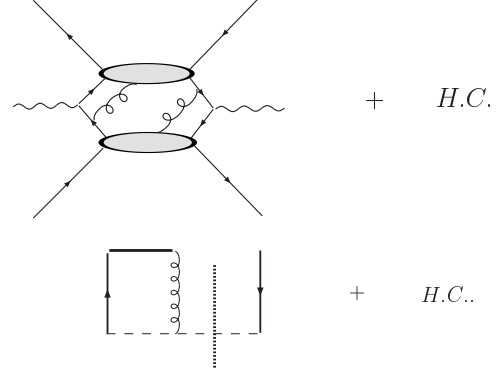


Figure 1. *Above:* Feynman diagram representing final state interactions giving rise to T -odd contribution to Drell-Yan Scattering. *Below:* Quark-target scattering amplitude depicting the T -odd contribution to the quark distribution function in the eikonal approximation.

struck quark line arising from the gauge link is indicated in Figure 1. Noting that parton intrinsic transverse momentum yielded a natural regularization for the moments of these distributions, we incorporated a Gaussian form factor into our model [29,30]. The result was

$$h_1^\perp(x, k_\perp) = \mathcal{N} \alpha_s M \frac{(1-x)(m+xM)}{k_\perp^2 \Lambda(k_\perp^2)} \mathcal{R}_h(k_\perp^2; x) \quad (6)$$

where \mathcal{R} is the regularization function

$$\mathcal{R}(k_\perp^2; x) = \exp^{-2b(k_\perp^2 - \Lambda(0))} \times (\Gamma(0, 2b\Lambda(0)) - \Gamma(0, 2b\Lambda(k_\perp^2))) .$$

\mathcal{N} is a normalization factor determined with respect to the unpolarized u -quark distribution, obtained from the zeroth moment of

$$f_1(x, k_\perp) = \frac{\mathcal{N}(1-x) \left((m+xM)^2 + k_\perp^2 \right)}{\Lambda^2(k_\perp^2)} \mathcal{R}_f(k_\perp^2),$$

normalized with respect to valence distributions in [51]. $\mathcal{R}_f(k_\perp^2; x) = \exp^{-2bk_\perp^2}$.

The asymmetry in the $p\bar{p}$ Drell-Yan process involves the convolution of the product of two T -odd distributions. The contribution to the double

T-odd azimuthal $\cos 2\phi$ asymmetry, ν in Eq. (4), in terms of initial and final (ISI/FSI) state interactions of active or “struck”, and fragmenting quark [29,30] is depicted in Figure 1. We

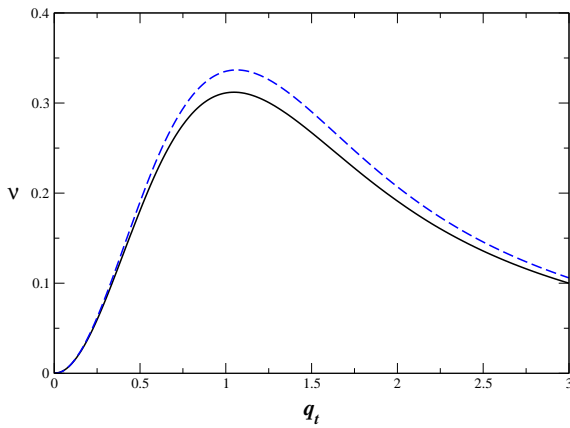


Figure 2. ν plotted as a function of q_T for $s = 50 \text{ GeV}^2$, x in the range $0.2 - 1.0$, and q ranging from $3 - 6 \text{ GeV}/c$.

have numerically performed the convolution integrals and obtained values of the asymmetry ν as a function of the variables, x , x_F , q_T , and q (or $m_{\mu\mu}$).

Before evaluating the convolution, the Drell-Yan kinematics demand some special attention. With x and \bar{x} being the fractional longitudinal momenta of the quark and antiquark, there are some constraints:

$$x\bar{x} = \tau = Q^2/s, \quad \frac{x - \bar{x}}{2} \equiv \eta = x_F/2 \quad \text{and} \\ x = \eta + \sqrt{\eta^2 + \tau}, \quad \bar{x} = -\eta + \sqrt{\eta^2 + \tau}. \quad (7)$$

Due to the constraint $x\bar{x} = q^2/s$ the allowed range of x is restricted for each q value, from $x_{min} = q^2/s$ to 1. Furthermore, evaluating the convolutions of $h_1^\perp h_1^\perp$ and $f_1 \bar{f}_1$ for a sampling of x will not treat the \bar{x} and the corresponding antiparticle structure functions symmetrically. So it is more appropriate to use the symmetrical variable, Feynman- x , $x_F = x - \bar{x}$ or $x = \frac{1}{2}(x_F + \sqrt{x_F^2 + 4q^2/s})$ and $\bar{x} = \frac{1}{2}(-x_F + \sqrt{x_F^2 + 4q^2/s})$. However, the allowed range of x_F depends on q

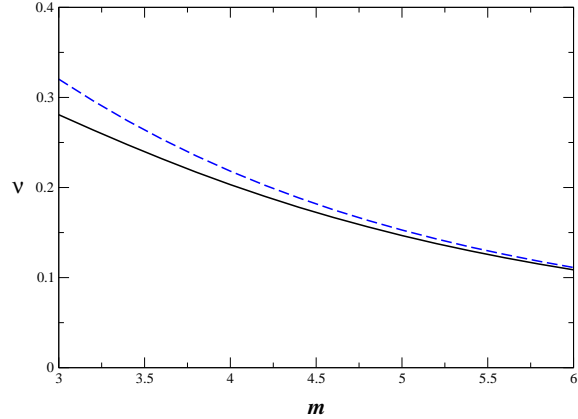


Figure 3. ν plotted as a function of $q = m_{\mu\mu}$ for $s = 50 \text{ GeV}^2$, x in the range $0.2 - 1.0$, and q_T ranging from $0 - 3 \text{ GeV}/c$.

(from $-1/2(1 - q^2/s)$ to $+1/2(1 - q^2/s)$)—the variables x_F and q are not orthogonal. Since we aim to present partially integrated values of ν , approximating experimentalists’ measurements, it is advantageous to work with orthogonal variables. We choose the variable

$$\zeta = \frac{1}{2} \frac{x_F}{(1 - q^2/s)}, \quad (8)$$

with range from $-\frac{1}{2}$ to $+\frac{1}{2}$, independent of q . Values of the asymmetry fill the rectangular space of variables, ζ, q, q_T . We have been careful with this choice because our model predictions have considerable structure in all 3 variables. Hence the meaning of a graph of $\nu(q)$ or $\nu(x)$ has particular significance when comparing to experimental data.

A crucial point in selecting these variables involves how experimenters determine various asymmetries and angular dependences, in order to maximize statistics when extracting possibly small effects like ν . Events appear distributed over allowed regions (modified by experimental acceptances) of all three variables along with the μ pair angular variables, of course. To obtain the dependence on one variable, large bins are defined and event numbers averaged over those bins. How are those results to be compared with theoretical predictions [52] ? The two experiments

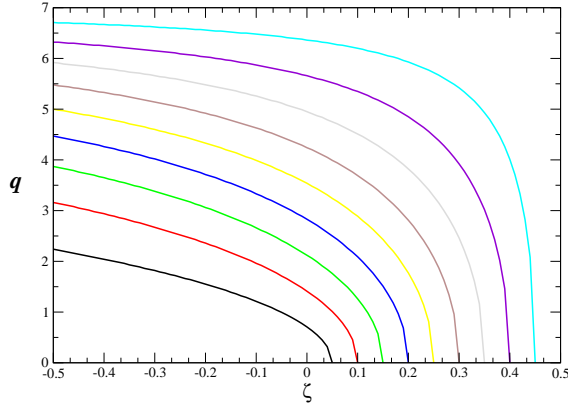


Figure 4. Contours of constant x as a function of ζ and q which ranges from 0 to 3 GeV/c.

for which data have been published have different ranges of variables [2,3]. The binning procedures are not easily compared. To be most general and adaptable for future experimental comparisons we have determined the value of ν as a function of ζ, q, q_T . We then integrate over pairs of those variables for particular ranges of the variables. At $s = 50 \text{ GeV}^2$ we take $q_T \leq 3 \text{ GeV/c}$ and $3 \text{ GeV/c} \leq q \leq 6 \text{ GeV/c}$, while ζ always varies from $-1/2$ to $+1/2$.

For $\nu(q_T)$ and $\nu(q)$ the resulting values are shown in Figures 2 and 3. There is a corresponding $\nu(\zeta)$ shown in Figure 5. To connect with the x or x_F dependence we have to take the q dependence into account. For any q_T the fixed x_F values form contours in the ζ, q plane (see Figure 4). So an integral of ν over q for a fixed x_F follows the relevant contour in ζ, q and has a limit on $\tau = q^2/s$ of $(1 - \frac{x_F}{2\zeta})$. This limits the range of the q integral until the limiting value of the range at $q = 6 \text{ GeV/c}$ for $s = 50 \text{ GeV}^2$. Similarly, for any q_T the fixed x values form asymmetrical contours in the ζ, q plane as shown in Figure 4. The limit on τ for a fixed x will be $x(\frac{2\zeta-x}{2\zeta x-1})$. The resulting values of $\nu(x)$ are shown in Figure 6. Finally, in Figure 7 we plot the leading twist contribution to ν as a function of x_F .

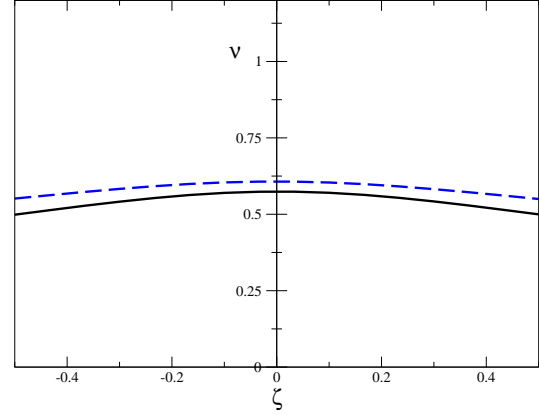


Figure 5. ν plotted as a function of ζ for $s = 50 \text{ GeV}^2$, q_T ranging from 3 to 6 GeV/c and q from 0 to 3 GeV/c.

4. T -Even Contribution

Long before the realization that there is a leading twist 2 contribution to the Drell-Yan azimuthal asymmetry, it was proposed by Collins and Soper [42] that the spin independent, transverse momentum dependent distributions f_1 and \bar{f}_1 could contribute via Eq. (3). It is important to compare this *kinematic* twist 4 contribution to the leading twist contribution (Eq. (4) shown above. We combined both convolutions to determine the magnitude of the shift. The additional contribution for $s = 50 \text{ GeV}^2$ to each of the partially integrated functions ν is shown in Figures 2,3,5,6 as slightly higher curves. At most the additional contribution is around 3–4%. For higher s values the effect is even smaller, as expected [34].

5. Conclusion

A perusal of the figures shows that the $\cos 2\phi$ azimuthal asymmetry ν is not small at center of mass energies of 50 GeV^2 . We estimated the leading twist 2 and twist 4 contributions [34]. In Figure 2, the T -odd portion contributes about 30% with an additional 3% from the sub-leading T -even piece. The distinction between the leading order T -odd and sub-leading order T -even con-

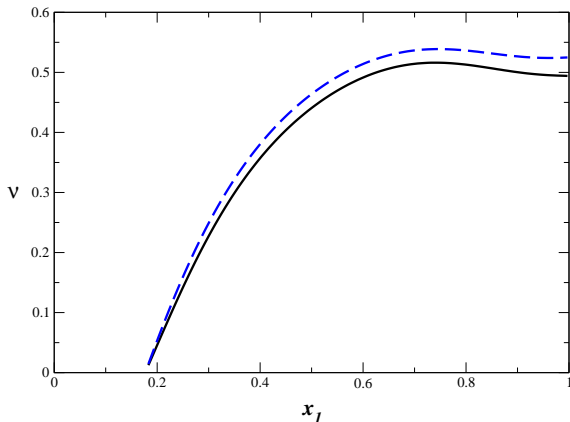


Figure 6. ν plotted as a function of x for $s = 50 \text{ GeV}^2$ q_T ranging from 3 to 6 GeV/c and q from 0 to 3 GeV/c.

tributions diminish at center of mass energy of $s = 500 \text{ GeV}^2$ [34]. In Figure 6, ν is plotted versus x at $s = 50 \text{ GeV}^2$, where q_T ranges from 2 to 4 GeV. Again the higher twist contribution is small.

Thus, aside from the competing T -even effect, the experimental observation of a strong x -dependence would indicate the presence of T -odd structures in *unpolarized* Drell-Yan scattering, implying that novel transversity properties of the nucleon can be accessed *without invoking beam or target polarization*.

It should be noted that at order α_s a complete analysis for the full range of q_T would entail including gluon bremsstrahlung contributions [41]. Furthermore, collinear Sudakov corrections have not been accounted for here [53]. A thorough explication of Drell-Yan dynamics would require more care with regions in which divergent contributions become important to address. For this study, however, we have considered the implications of our model, unencumbered by subtleties at the edges of the phase space on which we concentrate.

We conclude that T -odd correlations of intrinsic transverse quark momentum and transverse spin of quarks are intimately connected with studies of the $\cos 2\phi$ azimuthal asymmetries in $p\bar{p}$ -Drell-Yan scattering. Due to the dominance of

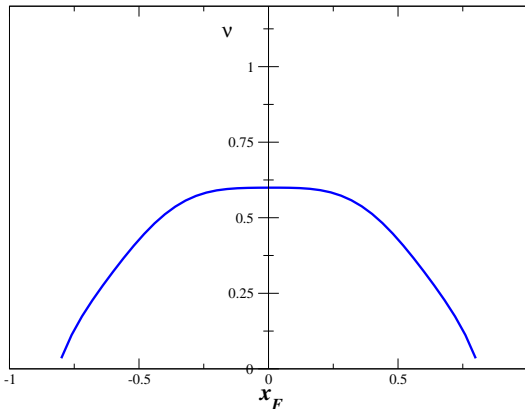


Figure 7. The leading twist contribution to ν plotted as a function of x_F for $s = 50 \text{ GeV}^2$ q_T ranging from 3 to 6 GeV/c and q from 0 to 3 GeV/c.

valence quark effects we estimate that the proposed proton anti-proton experiments at GSI [50] provide an excellent opportunity to study the role that T -odd correlations play in characterizing intrinsic transverse spin effects within the proton.

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